Carbon nanotubes as ultra-high quality factor mechanical resonators — and much more!

Andreas K. Hüttel

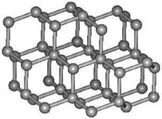
Kavli Institute for Nanoscience,
Technische Universiteit Delft, Netherlands

Institute for Experimental and Applied Physics,
Universität Regensburg, Germany

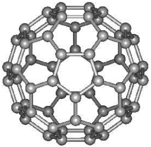
Condensed Matter and Materials Physics (CMMP10)
University of Warwick, Coventry, UK

14 December 2010

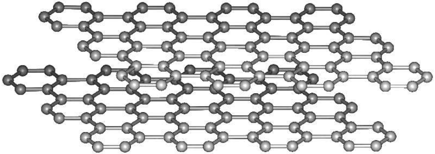
Carbon nanotubes: a more exciting (and not so flat) form of carbon



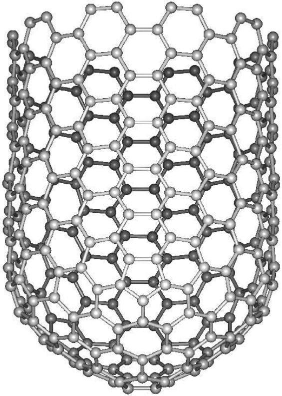
diamond



fullerene (C_{60})



graphite / graphene



nanotube

Mechanical properties of carbon nanotubes

- stiffer than steel
- resistant to damage from physical forces
- very light

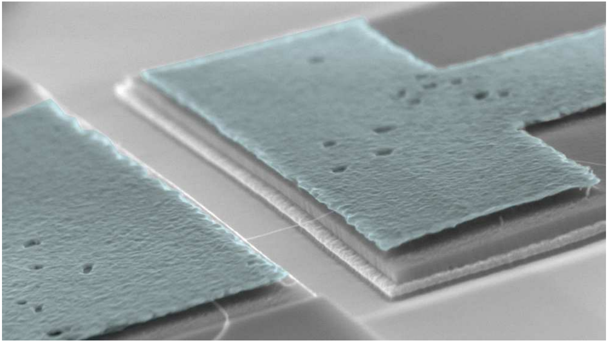
- Young's modulus $E = \frac{F/A}{\Delta L/L}$:

  $E_{\text{CNT}} \simeq 1.2\,\text{TPa}, \quad E_{\text{steel}} \simeq 0.2\,\text{TPa}$
- Density:

  $\rho_{\text{CNT}} \simeq 1.3\,\frac{\text{g}}{\text{cm}^3}, \quad \rho_{\text{Al}} \simeq 2.7\,\frac{\text{g}}{\text{cm}^3}$

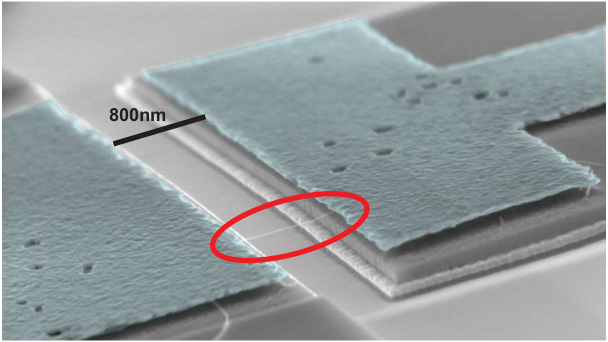
- (still) "material of dreams"

Doubly clamped nanotube resonators



nanotube is suspended like a guitar or violin string
low mass, high stiffness $\longrightarrow$ high resonance frequency, large quantum effects
single clean macromolecule $\longrightarrow$ low dissipation???

Doubly clamped nanotube resonators

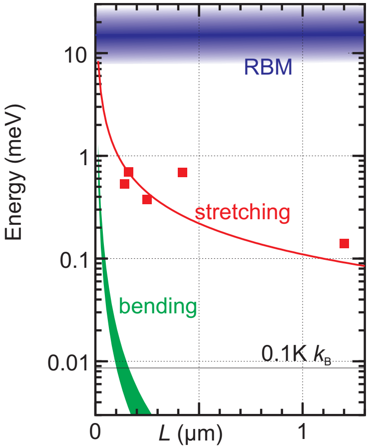


nanotube is suspended like a guitar or violin string

low mass, high stiffness $\longrightarrow$ high resonance frequency, large quantum effects

single clean macromolecule $\longrightarrow$ low dissipation???

Vibration modes of carbon nanotubes



- stretching (longitudinal) mode:

  $h\nu \propto L^{-1}$

  $h\nu = 1100 \ldots 110\,\mu$eV,

  $\nu = 270 \ldots 27\,$GHz

  (for 100 nm . . . 1 μm)

- bending (transversal) mode:

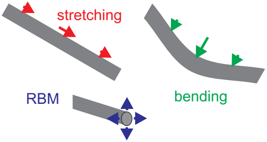
  $h\nu \propto L^{-2}$

  $h\nu = 10 \ldots 0.1\,\mu$eV,

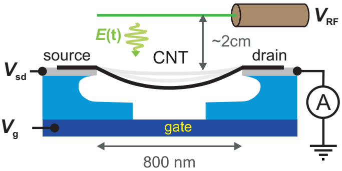
  $\nu = 2.4\,$GHz$\ldots 24\,$MHz

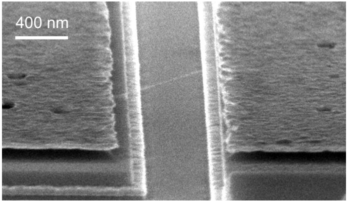
  (for 100 nm . . . 1 μm)

  $h\nu \propto d$, also tension-dependent



Chip fabrication and measurement setup





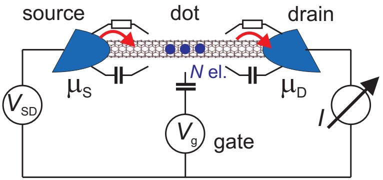
- First make chip (Pt electrodes, trench)
- Then CVD-grow nanotubes across electrodes
- Back gate connected to a gate voltage source V_g
- RF antenna suspended $\sim 2\,\text{cm}$ above chip
- Dilution refrigerator ($T \simeq 20\,\text{mK}$)
- Only dc measurement

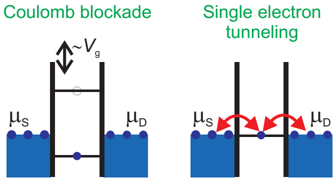
G. A. Steele *et al.*, Nature Nanotech. **4**, 363 (2009); AKH *et al.*, Nano Lett. **9**, 2547 (2009)

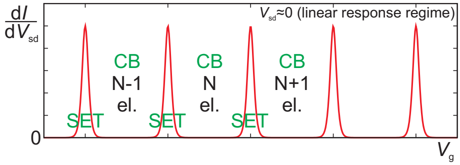
Low-temperature transport: Coulomb blockade

dilution refrigerator $T \lesssim 20\,\mathrm{mK}$

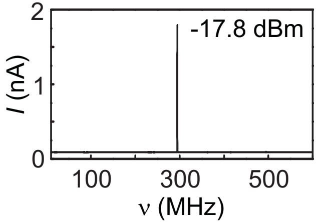
- Tunnel barriers between leads and nanotube
- Low temperature $k_B T \ll e^2/C$: formation of a quantum dot

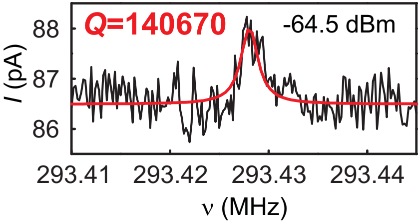


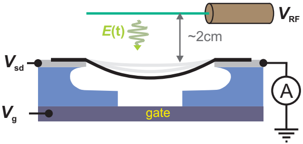




Fixed V_g and V_{SD}, sweep of RF signal frequency

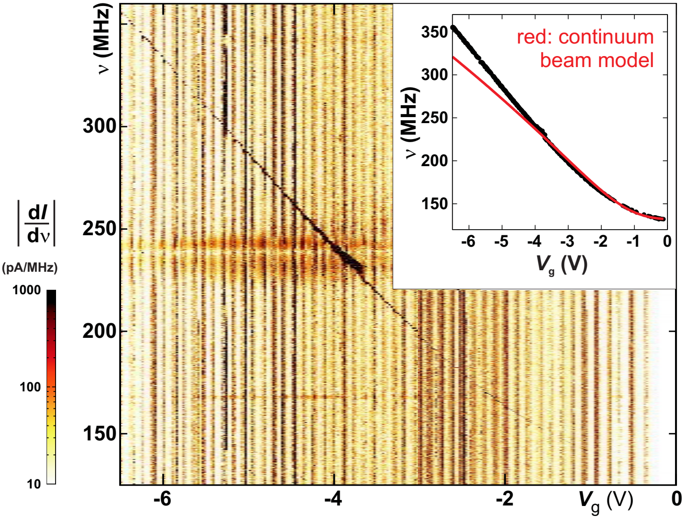






- Sharp resonant structure in $I_{dc}(\nu)$
- Very low driving power required
- High $Q = \nu / \Delta\nu \quad (\Delta\nu = \text{FWHM})$

V_g dependence — this is really a mechanical resonance!

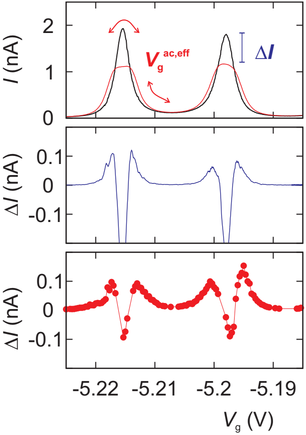


larger $|V_g|$ ⟶ increased tension ⟶ higher frequency ν

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

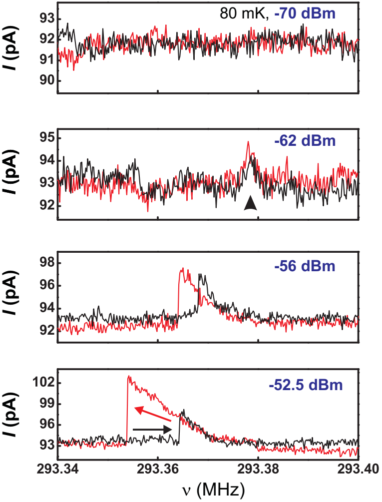
Detection mechanism — mechanically induced averaging

- at resonant driving the nanotube position oscillates
- oscillating C_g
  $\longrightarrow$ fast averaging over $I(V_\mathrm{g})$



- black line: dc measurement $I(V_\mathrm{g})$
- red line: this numerically averaged
- blue: difference, effect of averaging
- red points: measured peak amplitude in $I(\nu)$, for different values of V_g

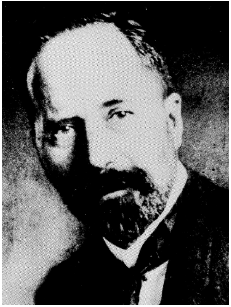
Driving into nonlinear response...



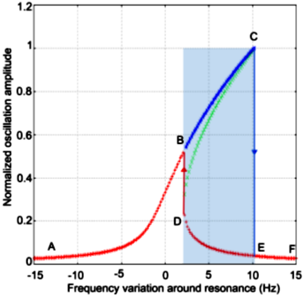
- same temperature
- same working point V_g, V_{SD}
- low driving power:
  symmetric, “linear” response
- high driving power:
  asymmetric response, hysteresis
  Duffing-like oscillator

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

Georg Duffing (1861 – 1944) and his oscillator



- Driven mechanical oscillator with non-linear response
- Response becomes bistable $\rightarrow$ large or small amplitude
- Switching between branches

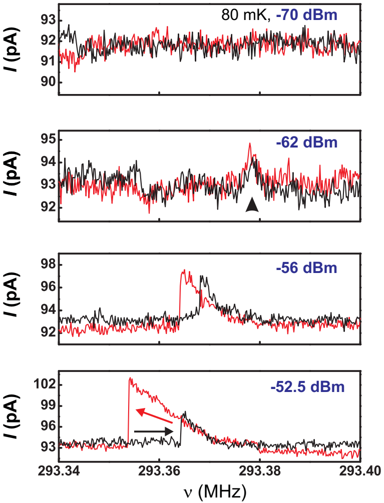


Duffing differential equation:

$$m\ddot{x} + cx + bx^3 = F \sin \omega t$$

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

Driving into nonlinear response...



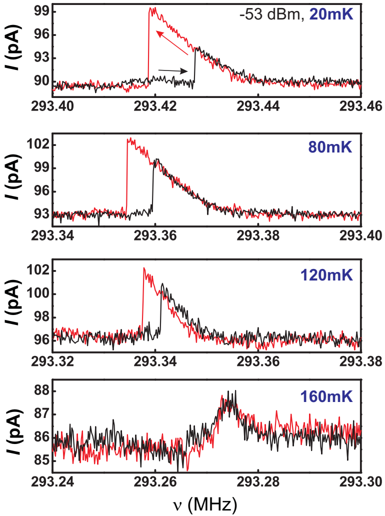
- same temperature
- same working point V_g, V_{SD}

- low driving power:
  symmetric, "linear" response

- high driving power:
  asymmetric response, hysteresis
  Duffing-like oscillator

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

... and then increasing the temperature



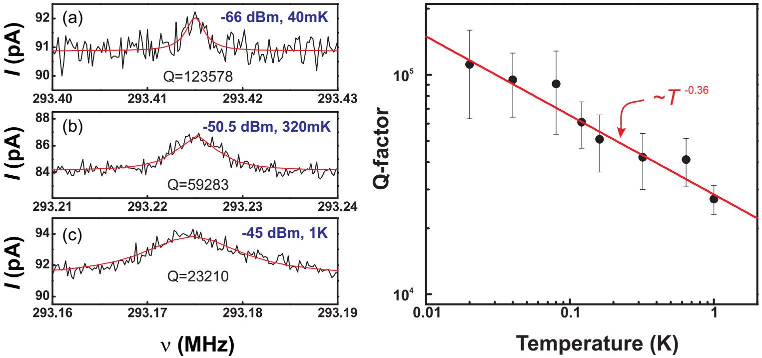
- same driving power
- same working point V_g, V_{SD}

- low temperature:
  - asymmetric response, hysteresis
  - Duffing-like oscillator

- high temperature:
  - symmetric, “linear” response
  - peak broadening

AKH *et al.*, Nano Lett. **9**, 2547 (2009)

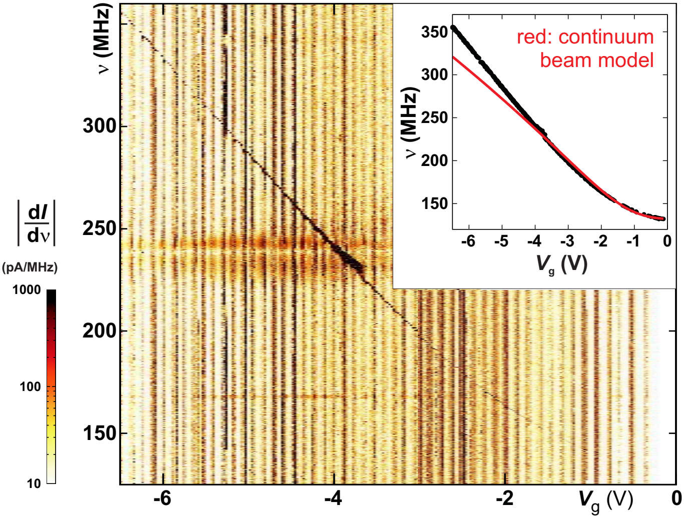
Temperature dependence of Q



$Q(T)$ fits power law prediction for intrinsic dissipation in nanotube

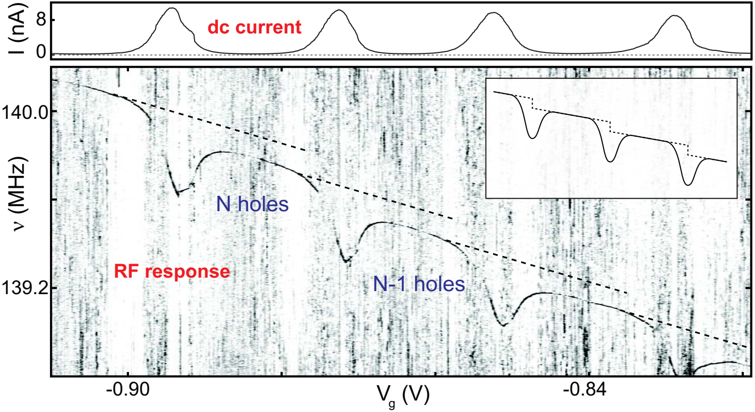
⟶ H. Jiang *et al.*, Phys. Rev. Lett. **93**, 185501 (2004)

V_g dependence — this is really a mechanical resonance!



larger $|V_g|$ ⟶ increased tension ⟶ higher frequency ν

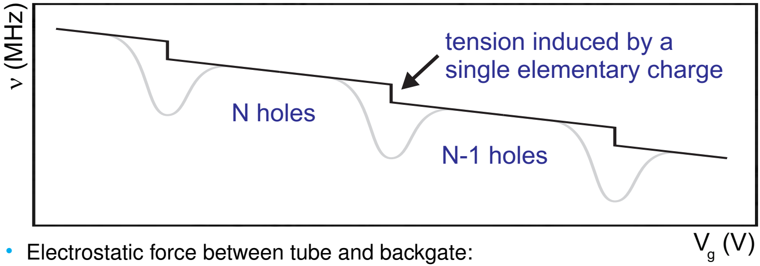
Detailed $\nu(V_g)$: with current, frequency decreases



"Coulomb blockade oscillations of mechanical resonance frequency"

electrostatic contribution to spring constant

Model for $\nu(V_g)$ – part I: “slope and steps”



- Electrostatic force between tube and backgate:

$$F_{dot} = \frac{1}{2}\frac{dC_g}{dz}\left(V_g - V_{dot}\right)^2$$

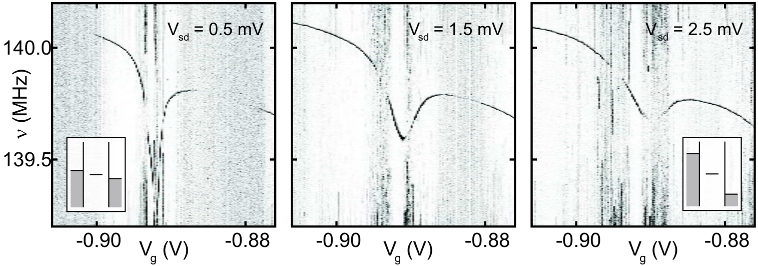
- Quantum dot voltage:

$$V_{dot} = \frac{C_g V_g + q_{dot}}{C_{dot}}, \qquad q_{dot}(q_c) = -|e|\langle N\rangle(q_c), \qquad q_c = C_g V_g$$

- Overall slope: continuous increase of voltage V_g on gate
- Steps: discrete change of V_{dot} (single elementary charges!)

G. A. Steele, AKH, *et al.*, Science **325**, 1103 (2009)

Model for $\nu(V_g)$ – part II: "steps become dips"



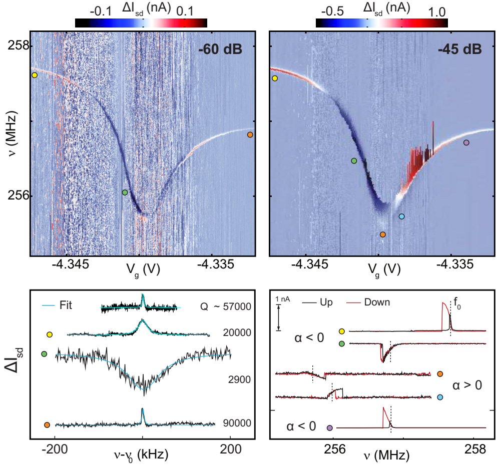
- $q_c = C_g(z) V_g$ is function of z
- Electrostatic contribution to spring constant:

$$k_{dot} = -\frac{dF_{dot}}{dz} = \frac{V_g(V_g - V_{dot})}{c_{dot}} \left(\frac{dC_g}{dz}\right)^2 \left(1 - |e|\frac{d\langle N\rangle}{dq_c}\right)$$

- Always negative, always decreasing frequency

G. A. Steele, AKH, *et al.*, Science **325**, 1103 (2009)

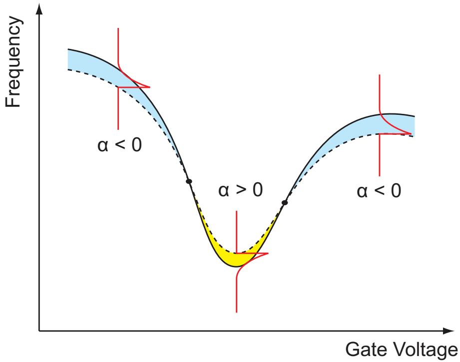
Also mechanical *Q* and nonlinearity dominated by current



- Dissipation whenever charge can fluctuate
- *Q* decreases on SET peaks

- Nonlinearity dominated by tunneling
- Switches between weakening and softening spring

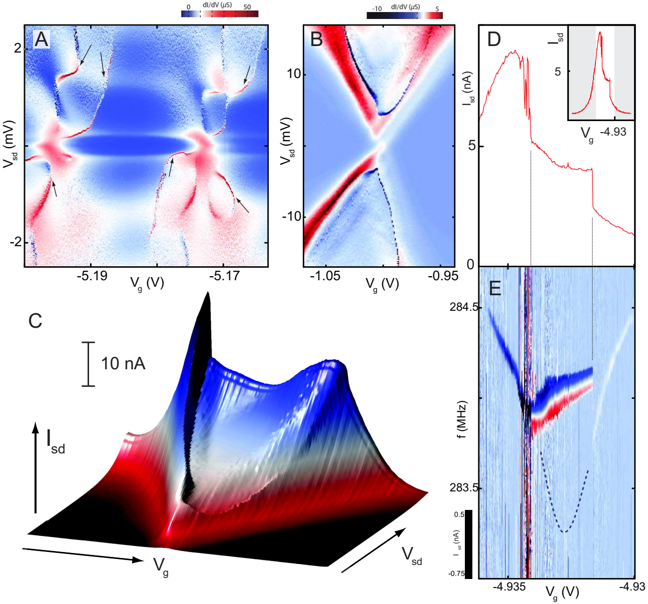
Interaction-induced nonlinearity $\alpha(V_g)$



$$\alpha_{\text{dot}} = -\frac{d^3 F}{dz^3} = \frac{d^2}{dz^2} k_{\text{dot}}(q_c) = V_g^2 \left(\frac{dC_g}{dz}\right)^2 \frac{d^2 k_{\text{dot}}}{dq_c^2}$$

The sign of α_{dot} follows the sign of the curvature of k_{dot}.

Self-excitation of the resonator



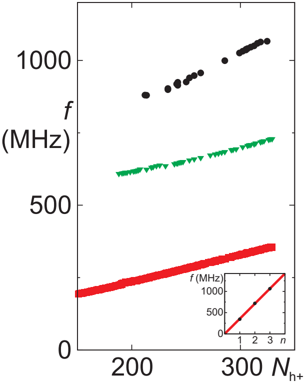
G. A. Steele, AKH, *et al.*, Science **325**, 1103 (2009); Usmani *et al.*, PRB **75**, 195312 (2007)

What do we have so far?

- Mechanical resonator, 120 MHz $\lesssim \nu \lesssim$ 360 MHz, $Q \lesssim 150000$
- Easy driving into nonlinear oscillator regime
- Single-electron steps of the resonance frequency
- Backaction of single electron tunneling on ν, Q, nonlinearity

- Estimated motion amplitude at resonant driving $\sim$ 250 pm
  compare thermal motion 6.5 pm, zero-point motion 1.9 pm
- Application as mass sensor: sensitivity $4.2 \frac{u}{\sqrt{\text{Hz}}}$
- Without driving: mechanical thermal occupation $n \simeq 1.2$

Higher frequency (I): higher vibration modes

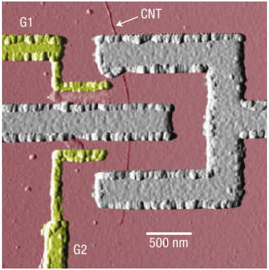


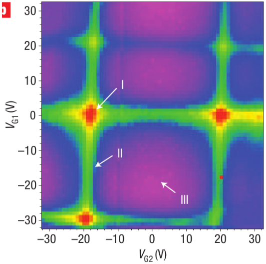
- higher harmonics visible too
- dc current signal is smaller
  (node(s) in nanotube motion, smaller change in total capacitance)
- at high tension, integer frequency multiples
  (expected for a string resonator)

Higher frequency (II): just make it shorter!

:) ongoing work in Delft and Regensburg :)

Going super





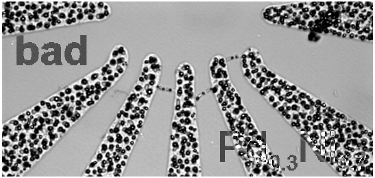
- Nanotubes can carry supercurrents via proximity effect
- Use superconducting electrodes
- Cooper pair tunneling
- Nanotube SQUIDs, ac Josephson effect, intrinsic cooling of the vibration, ...

- image: example for beautiful (non-suspended) hybrid device

- Superconducting support and control electronics!

images from J. P. Cleuziou *et al.*, Nat. Nano. **1**, 53 (2006)

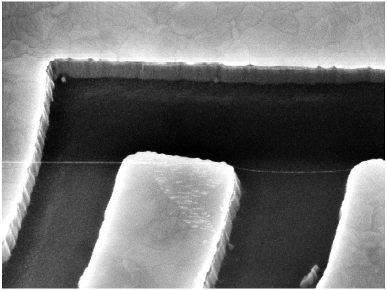
Pitfalls and problems for *ultra-clean samples*

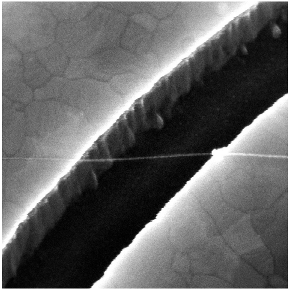


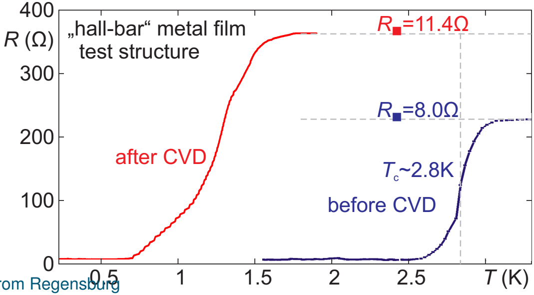
- need to first prepare on-chip infrastructure: contacts, gates, trenches, ...
- then grow nanotubes across the chip with CVD as last step
- 10min, 900°C, CH_4 and H_2: for a metal thin film "as bad as it gets"

- melting, recrystallization
  - → deformation, loss of conductivity
- hydrogen / carbon storage in metal
  - → lowering of superconductor T_c
- influence of metal on nanotube growth?
- properties of nanotube–metal contact?

but... it seems to be working





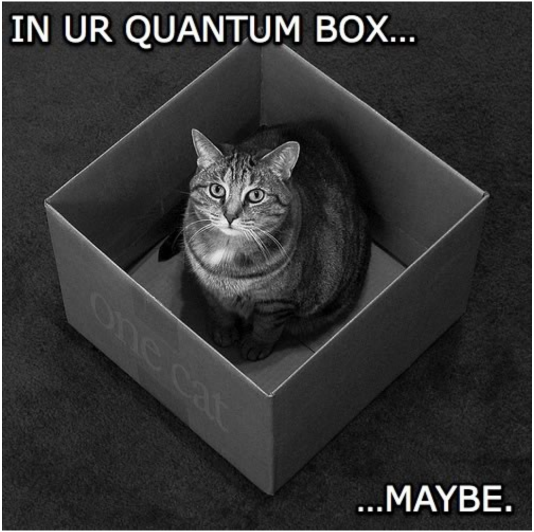


∼5 day old SEM images from Regensburg

lots of opportunities

- beam resonator in quantum mechanical ground state
- transition classical – quantum harmonic oscillator
- quantum nonlinear resonator properties (many theory predictions!)
- ...
- ...
- ...

Go quantum limit!



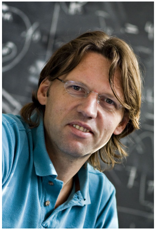
The old team at TU Delft

Thanks!

Gary Steele

Benoit Witkamp

Menno Poot



Leo Kouwenhoven

Harold Meerwaldt

Herre van der Zant

My new team at Uni Regensburg

Thanks!

Daniel Schmid

Dominik Preusche

Peter Stiller

you?

Christoph Strunk

and everyone else!